Parity Violation in Bottom Quark Pair Production at Polarized Hadron Colliders

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Abstract

Parity violation induced by the chromo-anapole form factor of the bottom quark, generated from weak corrections, is studied in polarized hadron collisions. The forward-backward asymmetry in the bottom quark pair production at polarized pp and $p\bar{p}$ colliders is evaluated in the Standard Model and in a Two Higgs Doublet Model to examine the effects of parity violation. In the models studied, promising results are found for polarized $p\bar{p}$ colliders.

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1 Introduction

The large production cross section of bottom quark pairs ($b\bar{b}$) at polarized hadron colliders [1, 2] coupled with the relatively long lifetime of the b-quark, implies that detailed experimental study of the properties of the b-quark at those facilities could also be very useful. Since the CKM mixing angle V_{tb} is close to one, the b quark couples rather readily to the virtual top quark in loop diagrams. Now the top quark is so heavy ($m_t \sim 175$ GeV) [3, 4] that the b-quark becomes very sensitive to electroweak radiative corrections as these corrections often tend to grow with the virtual quark mass [5]. Precision studies of the b's are thus very useful in testing the Standard Model (SM) and in searching for new physics.

In the hadronic environment, while the production cross sections are high, a quantitative understanding of the effects of QCD can be a very difficult challenge. For this reason, in testing the SM and in searching for clues of new physics, it is perhaps better to focus on observables that tend to be robust to QCD corrections. For that reason, in general, the production cross section is not a good observable. We propose to focus instead on signatures of parity violation in b-quark production since QCD corrections cannot generate parity violation. Parity violating asymmetries that are ratios of cross-sections should be less sensitive to QCD corrections as well as to the uncertainties in the parton distribution functions. Furthermore, in study of parity violation, one may be able to make use of polarized incident $p(\bar{p})$ beams [6]. We will concentrate on one type of parity violating observable, that is the forward-backward asymmetry. In its differential form, it is defined as:

$$\delta\mathcal{A}(M_{b\bar{b}}) \equiv \frac{d\sigma_F/dM_{b\bar{b}} - d\sigma_B/dM_{b\bar{b}}}{d\sigma_F/dM_{b\bar{b}} + d\sigma_B/dM_{b\bar{b}}} \tag{1}$$

where the subscripts F and B stand for the forward and the backward hemispheres respectively.

For the reactions of interest to us, i.e. $pp \rightarrow b\bar{b} + X$ or $p\bar{p} \rightarrow b\bar{b} + X$, we consider

two sources of contributions to such a parity violating observable. These are the chromo-anapole form factor of the $gb\bar{b}$ vertex (note $g \equiv gluon$) and the tree level electroweak process $q\bar{q} \rightarrow Z \rightarrow b\bar{b}$. The latter contribution (Z exchange) is significant only when the invariant mass ($M_{b\bar{b}}$) of the $b\bar{b}$ pair is close to the Z mass (M_Z). It can be removed, if necessary, by imposing an appropriate cut on the $M_{b\bar{b}}$. Thus, the chromo-anapole form factor is a very important contributor to the parity violating signal and consequently it is our primary focus.

Recently, several suggestions have been made to study parity violation asymmetries in polarized hadron collisions for (1) the production of one jet, two jets, and two jet plus photon in the SM [7]; (2) the production of $W^{\pm}$ and Z in the SM [8]; and (3) the inclusive production of one jet with a new handed interaction between subconstituents of quarks [9]. These works primarily deal with interference of electroweak and strong interactions on light quarks.

In this Letter, we present the first study on parity violation generated from one loop weak corrections to bottom quark pair production at polarized hadron colliders. The key difference with the works in Refs. [7, 8, 9] is, as alluded to in the opening paragraph, that the $b\bar{b}$ pair in the final state in our study is a very sensitive tool of the effects of the top quark which in turn is sensitive to non-standard effects. Specifically, we will evaluate the forward-backward asymmetry in the bottom quark pair production at polarized pp and $p\bar{p}$ colliders in the Standard Model and in a Two Higgs Doublet Model to examine the effects of parity violation from the interactions of $b\bar{b}$ with spin-1 and spin-0 fields.

2   Form Factors

Let us write the $gb\bar{b}$ vertex as

$$- ig_s \bar{u}(p_1) T^a \Gamma^\mu v(p_2) \tag{2}$$

where g_s = the strong coupling, T^a = the SU(3) matrices, $u(p_1)$ and $v(p_2)$ are the Dirac spinors of b and $\bar{b}$ with outgoing momenta p_1 and p_2 and $k = p_1 + p_2$ is the momentum of the gluon. At the tree level $\Gamma_0^\mu = \gamma^\mu$. The 1-loop vertex function can be expressed as

$$
\begin{aligned}
\Gamma^\mu &= \gamma^\mu [A(k^2) - B(k^2)\gamma_5] \\
&\quad + (p_1 - p_2)^\mu [C(k^2) - D(k^2)\gamma_5] \\
&\quad + (p_1 + p_2)^\mu [E(k^2) - F(k^2)\gamma_5]
\end{aligned}
\tag{3}
$$

Current conservation demands that $E = 0$ and $B = -k^2 F(k^2)/2m_b$, where $k = p_1 + p_2$ and $k^2 = M_{b\bar{b}}^2 = \hat{s}$ in the $b\bar{b}$ center of mass (CM) frame. Applying the Gordon identities we can re-write

$$
\begin{aligned}
\Gamma_\mu &= F_1(k^2)\gamma^\mu - F_2(k^2)i\sigma^{\mu\nu}k_\nu \\
&\quad + a(k^2)\gamma_\nu\gamma_5(k^2 g^{\mu\nu} - k^\mu k^\nu) + d(k^2)i\sigma^{\mu\nu}k_\nu\gamma_5
\end{aligned}
\tag{4}
$$

where $F_1(k^2) = A(k^2) + 2m_b C(k^2)$, $F_1(0)$ = the chromo-charge; $F_2(k^2) = C(k^2)$, $F_2(0)$ = the anomalous chromo-magnetic moment; $a(k^2) = -B(k^2)/k^2 = F/(2m_b)$, $a(0)$ = chromo-anapole moment; $d(k^2) = D(k^2)$, and $d(0)$ = the chromo-electric dipole moment.

In the SM, the dominant one loop weak corrections that contribute to the chromo-anapole moment arise from diagrams with the W^+ and its Goldstone counterpart, the G^+. In many extensions of the SM, $e.\,g.$ in models which contain more than one doublets of Higgs, there are charged Higgs bosons ($H^\pm$) contributing to the chromo-anapole form factor of fermions at the one-loop order. As is well known the simplest of such extensions consists of two Higgs doublets [10] ϕ_1 and ϕ_2 with vacuum expectation values (VEVs) v_1 and v_2. After symmetry breaking, there remain five physical Higgs bosons [11]: a pair of singly charged Higgs bosons $H^\pm$, two neutral CP-even scalars H (heavier) and h (lighter), and a neutral CP-odd pseudoscalar A. The ratio of the two VEVs is usually expressed as $\tan\beta \equiv v_2/v_1$.

In our analysis, we have considered such a Two Higgs Doublet Model (THDM) with the Yukawa interactions of model II [12], which is required in the minimal supersymmetric model (MSSM)[1]. [11] In this model, one doublet (ϕ_1) couples to down-type quarks and charged leptons while the other (ϕ_2) couples to up-type quarks and neutrinos. The one loop weak corrections from diagrams with the W^+, the G^+ and the H^+, yield dominant contribution to the b quark anapole moment from the virtual top quark in the loop. In our calculations of these corrections we will set $V_{tb} = 1$ and also we will ignore CP violating effects. We have employed the 't Hooft–Feynman gauge for loop calculations with $M_{G^\pm} = M_W$.

The forward-backward asymmetry in $b\bar{b}$ production is primarily driven by $\mathrm{Re}B(k^2)$ which is related to the chromo-anapole form factor $(a(k^2))$ via $B(k^2) = -k^2a(k^2)$. Therefore, in Fig. 1 we present $\mathrm{Re}B(k^2)$ coming separately from diagrams with the $G^\pm(B_G)$, the $W^\pm(B_W)$ and the Z as well as the total contribution in the SM. As an illustration of a beyond the SM effect, we also show $\mathrm{Re}B(k^2)$ for THDM for $M_{H^+} = 200$ GeV and various values of $\tan\beta$. The Z boson exchange contribution to the b-chromo-anapole moment is very small since the coupling product $2g_V^b g_A^b$ is very small. The form factor $\mathrm{Re}B(k^2)$ is enhanced near $k^2 \sim 4m_t^2$, where $k^2 = \hat{s} = M_{b\bar{b}}^2$, due to the $t\bar{t}$ threshold which appears in diagrams with charged boson (*i. e.* $W^\pm$ or $H^\pm$) exchanges. Since $B(k^2) = -k^2a(k^2) = -\hat{s}a(\hat{s})$, its value is expected to grow with $M_{b\bar{b}}$. From Fig. 1 we see that numerically this increase sets in for $M_{b\bar{b}} \gtrsim 500$ GeV.

In the THDM, the form factor $B(k^2)$ gets an additional contribution, $B_H(k^2)$, from the charged Higgs boson. Clearly B_H is a function of M_{H^+} and $\tan\beta$, being proportional to $\cot^2\beta\{1-[(m_b/m_t)\tan^2\beta]^2\}$. Therefore, it has the same sign as B_G for $\tan\beta < \sqrt{m_t/m_b} \sim 6$, but has an opposite sign for $\tan\beta > \sqrt{m_t/m_b}$. Thus the effects of parity violation are

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[1] In the MSSM, though,there are additional contributions to the chromo-anapole moment from loop diagrams with the charginos and the squarks as well.

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enhanced in the THDM if $\tan\beta$ is less than $\sqrt{m_t/m_b}$. For $\tan\beta = \sqrt{m_t/m_b}$, the B_H vanishes and the total $B(k^2)$ becomes that of the SM.

3 Forward Backward Asymmetry

Let us define the cross section for the sub-process, $q\bar{q} \to b\bar{b}$, in each helicity state of quarks in the initial state as

$$\hat{\sigma}_{\lambda_1\lambda_2} \equiv \hat{\sigma}(q_{\lambda_1}\bar{q}_{\lambda_2} \to b\bar{b}) \tag{5}$$

where $\lambda_{1,2}$ represents a right-handed (R) or a left-handed (L) helicity of the quark and the antiquark. The cross sections in the forward $(0 \leq \theta \leq \pi)$ and the backward $(-\pi \leq \theta \leq 0)$ directions are defined as

$$
\begin{aligned}
\hat{\sigma}^F_{\lambda_1\lambda_2} &\equiv \int_0^1 \frac{d\hat{\sigma}_{\lambda_1\lambda_2}}{dz}dz \\
\hat{\sigma}^B_{\lambda_1\lambda_2} &\equiv \int_{-1}^0 \frac{d\hat{\sigma}_{\lambda_1\lambda_2}}{dz}dz \\
\hat{\sigma}_{\lambda_1\lambda_2} &= \hat{\sigma}^F_{\lambda_1\lambda_2} + \hat{\sigma}^B_{\lambda_1\lambda_2} \\
\Delta\hat{\sigma}_{\lambda_1\lambda_2} &= \hat{\sigma}^F_{\lambda_1\lambda_2} - \hat{\sigma}^B_{\lambda_1\lambda_2}
\end{aligned}
\tag{6}
$$

where $z = \cos\theta$, with θ being the scattering angle of the b in the $b\bar{b}$ center of mass frame, $\hat{\sigma}$ is the total cross section of the $q\bar{q}$ subprocess and $\Delta\hat{\sigma}$ is the difference of the cross sections in the forward and the backward directions of the subprocess. (Note that variables in the CM frame of the $q\bar{q}$ subprocess are denoted with a ^ on top of them).

The tree level expressions for these cross sections are

$$
\begin{aligned}
\hat{\sigma}^0_{RL} &= \hat{\sigma}^0_{LR} \\
&= \frac{g_s^4}{27\pi\hat{s}}\left(1 + \frac{2m_b^2}{s}\right) \\
\hat{\sigma}^0_{LL} &= \hat{\sigma}^0_{RR} = 0
\end{aligned}
\tag{7}
$$

At the tree level, the difference of the cross sections in the forward and backward directions is zero in each helicity state of $q\bar{q}$ because parity is conserved in QCD.

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The one loop weak corrections to the $q\bar{q}$ cross section is

$$
\begin{aligned}
\hat{\sigma}_{RL}^1 &= \hat{\sigma}_{LR}^1 \\
&= \frac{g_s^4}{27\pi\hat{s}}[Re(A)(2 + \frac{4m_b^2}{\hat{s}}) + Re(C)(m_b)(-1 + \frac{4m_b^2}{\hat{s}})]
\end{aligned}
\tag{8}
$$

And the difference of $q\bar{q}$ cross sections in the forward and backward directions is

$$
\begin{aligned}
\Delta\hat{\sigma}_{RL} &= -\Delta\hat{\sigma}_{LR} \\
&= -\frac{g_s^4}{18\pi\hat{s}}\beta^2[Re(B)]
\end{aligned}
\tag{9}
$$

where $\beta = \sqrt{1 - 4m_b^2/\hat{s}}$ and A, B and C are form factors defined in Eq. 3. A nonzero $\Delta\hat{\sigma}_{RL}$ is of course a signature of parity violation.

In polarized pp and $p\bar{p}$ collisions, the differential cross section for the production of $b\bar{b}$ takes the form

$$
\begin{aligned}
\frac{d\sigma}{dx_1 dx_2} &= \hat{\sigma}_{RL}[q_R(x_1,\hat{s})\bar{q}_L(x_2,\hat{s}) + q_R(x_2,\hat{s})\bar{q}_L(x_1,\hat{s}] \\
&+ \hat{\sigma}_{LR}[q_L(x_1,\hat{s})\bar{q}_R(x_2,\hat{s}) + q_L(x_2,\hat{s})\bar{q}_R(x_1,\hat{s}] \\
&+ \hat{\sigma}_{RR}[q_R(x_1,\hat{s})\bar{q}_R(x_2,\hat{s}) + q_R(x_2,\hat{s})\bar{q}_R(x_1,\hat{s}] \\
&+ \hat{\sigma}_{LL}[q_L(x_1,\hat{s})\bar{q}_L(x_2,\hat{s}) + q_L(x_2,\hat{s})\bar{q}_L(x_1,\hat{s}]
\end{aligned}
\tag{10}
$$

where x_1 and x_2 are momentum fractions of the partons in the initial beam.

Parity violation can be studied at hadron colliders by using polarized initial beams, e.g. $p_R p_L$ or $p_R \bar{p}_L$ etc. Let us consider two hadron colliders with polarized beams (a) $p_R p_L$ and (b) $p_R \bar{p}_L$. With polarized pp or $p\bar{p}$ beams, we can define $q_i^+(x,\hat{s})$ [$q_i^-(x,\hat{s})$] to be the probability density [13] for a quark of flavor i and momentum fraction x with a helicity of the same [opposite] sign as the helicity of the proton. The differential cross section, $d\sigma_{RL}$ in polarized $p_R p_L$ collisions become

$$
\frac{d\sigma_{RL}}{dx_1 dx_2} = \frac{d\sigma_{LR}}{dx_1 dx_2}
$$

6

$$\begin{aligned}
&= \hat{\sigma}_{RL}[q^+(x_1, \hat{s})\bar{q}^+(x_2, \hat{s}) + q^-(x_2, \hat{s})\bar{q}^-(x_1, \hat{s}) \\
&\quad + q^-(x_1, \hat{s})\bar{q}^-(x_2, \hat{s}) + q^+(x_2, \hat{s})\bar{q}^+(x_1, \hat{s})] \\
\sigma_{RL} &= \int_{x_1^{min}}^{1} dx_1 \int_{x_2^{min}}^{1} dx_2 \frac{d\sigma_{RL}}{dx_1 dx_2}
\end{aligned} \tag{11}$$

For $gg \to b\bar{b}$, we need to sum over all helicity states: $g_R g_L$, $g_L g_R$ $g_R g_R$ and $g_L g_L$.

The difference of σ in the forward $(0 < \theta < \pi)$ and the backward $(-\pi < \theta < 0)$ directions at the $b\bar{b}$ CM frame in polarized $p_{\lambda_1} p_{\lambda_2}$ collisions are

$$\begin{aligned}
\frac{\delta\sigma_{RL}}{dx_1 dx_2} &= -\frac{\delta\sigma_{LR}}{dx_1 dx_2} \\
&= \Delta\hat{\sigma}_{RL}[q^+(x_1, \hat{s})\bar{q}^+(x_2, \hat{s}) - q^-(x_2, \hat{s})\bar{q}^-(x_1, \hat{s}) \\
&\quad - q^-(x_1, \hat{s})\bar{q}^-(x_2, \hat{s}) + q^+(x_2, \hat{s})\bar{q}^+(x_1, \hat{s})] \\
\Delta\sigma_{RL} &= \int_{x_1^{min}}^{1} dx_1 \int_{x_2^{min}}^{1} dx_2 \frac{\delta\sigma_{RL}}{dx_1 dx_2}
\end{aligned} \tag{12}$$

At high energy, parity violation from chromo-anapole form factor is expected to increase with $M_{b\bar{b}}$. It is therefore useful to examine the differential forward-backward asymmetry given in Eq. 1. The numerator has contribution only from $q\bar{q} \to b\bar{b}$, while the denominator has contributions from both $q\bar{q} \to b\bar{b}$ and $gg \to b\bar{b}$. Gluon fusion produces a large number of $b\bar{b}$ pairs, which tend to contribute significantly to the denominator of Eq. 1 thus reducing the signal for the parity violating asymmetry from $q\bar{q}$ in pp collisions. In $p\bar{p}$ collisions, the antiquark density is greatly enhanced, therefore, parity violation signals from $q\bar{q} \to b\bar{b}$ is much larger in $p\bar{p}$ than in pp collisions at the same energy. This differential asymmetry is presented in Figures 2 and 3 for polarized $p_R p_L$ and $p_R \bar{p}_L$ collisions at several values of energy. The parity violation signal peaks at the $M_{b\bar{b}} = 2m_t$ in the differential of forward-backward asymmetry versus $M_{b\bar{b}}$. Also shown is the same asymmetry in $q\bar{q} \to Z \to b\bar{b}$; it dominates if $M_{b\bar{b}}$ is close to M_Z, but becomes negligible for $|M_{b\bar{b}} - M_Z| > 10$ GeV.

The integrated forward-backward asymmetry is defined as

$$\mathcal{A} \equiv \frac{N_F - N_B}{N_F + N_B} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$N = \mathcal{L}\sigma \tag{13}$$

where N_F and N_B are the number of $b\bar{b}$ pairs in the forward and the backward directions; and $\mathcal{L}$ is the integrated luminosity. The statistical uncertainty ($\Delta\mathcal{A}$) and the statistical significance (N_S) of the integrated asymmetry are

$$\Delta\mathcal{A} \simeq \frac{1}{\sqrt{N_F + N_B}} \tag{14}$$

$$N_S \equiv \mathcal{A}/\Delta\mathcal{A}. \tag{15}$$

The difference ($\Delta\sigma$) and the total (σ) of the cross sections σ_F and σ_B with one loop weak corrections, as well as the integrated asymmetry ($\mathcal{A}$) and its statistical significance (N_S) are presented in Table 1 for an integrated luminosity of 10 fb^{-1} and 100 fb^{-1}. For $\sqrt{s} \geq 1$ TeV, this asymmetry might be visible with $\mathcal{L} = 100$ fb^{-1} and a cut on $M_{b\bar{b}}$. We find that requiring a higher $M_{b\bar{b}}$ can efficiently enhance the asymmetry from weak corrections in $q\bar{q} \rightarrow b\bar{b}$. A high $M_{b\bar{b}}$ cut not only reduces the cross section from gluon fusion it also reduces the asymmetry from $q\bar{q} \rightarrow Z \rightarrow b\bar{b}$ as well.

We close with two brief remarks.

1) In our calculations we have retained only the parity violating effects originating from $q\bar{q} \rightarrow b\bar{b}$. In principle, gluon fusion, i.e. $gg \rightarrow b\bar{b}$, can also contribute to parity violation due to electroweak corrections [14]. However, dimensional reasoning indicates that such contributions are probably small at lower energy, at least for $\sqrt{\hat{s}} \lesssim 2m_t$. In any case, it is very unlikely that the contribution to the forward backward asymmetry from such a source will cancel away the $q\bar{q}$ contribution for all values of $M_{b\bar{b}}$.

2) It would clearly be extremely interesting to consider these parity violating effects in other extensions of the SM; in particular in the MSSM. As we noted before, in MSSM, there will be additional loop contributions not contained in a THDM that could enhance the asymmetry [14].

4 Conclusions

To summarize, at a hadron collider with polarized pp and $\sqrt{s} = 500$ GeV (e.g. RHIC), parity violation in $b\bar{b}$ production will be dominated by $q\bar{q} \to Z \to b\bar{b}$. In polarized $p_R\bar{p}_L$ collisions with $\sqrt{s} \geq 1000$ GeV and enough integrated luminosity, it might be possible to observe parity violation signals from SM weak corrections in $b\bar{b}$ production. In the THDM with Model II Yukawa interactions, the chromo-anapole form factor of the bottom quark generated from leading weak corrections is enhanced for $\tan\beta$ close to one. It is enhanced by the factor $\cot^2\beta$ for $\tan\beta$ less than one. Therefore, the signal of parity violation in $b\bar{b}$ production is greatly enhanced for $\tan\beta \lesssim 1$ and M_{H^+} less than about 300 GeV.[2] The study of parity violation in $b\bar{b}$ production might provide a good opportunity to study new interactions between the third generation quarks and (charged) spin-0 as well as spin-1 bosons.

Acknowledgements

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[2] In the same model, parity violation in $t\bar{t}$ production [15], is greatly enhanced for $\tan\beta \gtrsim m_t/m_b$. In Ref. [15], parity violation in $t\bar{t}$ production was studied in unpolarized $p\bar{p}$ collisions.

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Tables

Table 1. The difference ($\Delta\sigma$) and the total (σ) of cross sections σ_F and σ_B, and the asymmetry of $p_R\bar{p}_L \to b\bar{b} + X$ as defined in Eq. 13 generated by weak corrections in (a) the SM and (b) the THDM with $M_{H^+} = 200$ GeV and $\tan\beta = 1$, for $\sqrt{s} = 500$ GeV with $M_{b\bar{b}} > 100$ GeV, $\sqrt{s} = 1$ TeV with $M_{b\bar{b}} > 200$ GeV and $\sqrt{s} = 2$ TeV with $M_{b\bar{b}} > 300$ GeV. Also shown is the statistical significance (N_S) for $\mathcal{L} = 10$ fb^{-1} and 100 fb^{-1}.

$\sqrt{s}$ (GeV)	$\Delta\sigma$ (pb)	$\sigma(q\bar{q})$ (pb)	$\sigma(gg)$ (pb)	$\mathcal{A}$ (%)	N_S (10 fb^{-1})	N_S (100 fb^{-1})
(a) SM						
500	-0.130	124	81.2	-0.063	0.91	2.9
1000	-0.081	22.9	17.2	-0.20	1.3	4.1
2000	-0.122	16.6	33.3	-0.25	1.7	5.5
(b) THDM						
500	-0.156	124	81.2	-0.076	1.1	3.4
1000	-0.106	22.9	17.2	-0.27	1.7	5.3
2000	-0.163	16.7	33.3	-0.33	2.3	7.3

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Figures

Fig. 1. The real part of the chromo-anapole form factor $B(\hat{s})$ as a function of $M_{b\bar{b}}$ from (a) the diagrams with G^+ (dash), the W^+ (dot-dash), the Z (dot) and the SM Total; and the THDM Total for $\tan\beta = 0.5, 1, 3, 10$ and 35, with (b) $m_{H^+} = 200$ GeV and (c) $m_{H^+} = 400$ GeV. Note that $\hat{s} = M_{b\bar{b}}$.

Fig. 2. The differential forward-backward asymmetry (δA) defined in Eq. 1 versus $M_{b\bar{b}}$, in polarized $p_R p_L$ collisions for (a) $\sqrt{s} = 500$ GeV (b) $\sqrt{s} = 1000$ GeV and (c) $\sqrt{s} = 2000$ GeV. This asymmetry has been evaluated using the (total) chromo-anapole form factor from leading weak corrections in the SM as well as in the THDM for $m_{H^+} = 200$ GeV and $\tan\beta = 0.5, 1$, and 35.

Fig. 3. The differential forward-backward asymmetry (δA) defined in Eq. 1 versus $M_{b\bar{b}}$, in polarized $p_R \bar{p}_L$ collisions for (a) $\sqrt{s} = 500$ GeV (b) $\sqrt{s} = 1000$ GeV and (c) $\sqrt{s} = 2000$ GeV. This asymmetry has been evaluated using the (total) chromo-anapole form factor from leading weak corrections in the SM as well as in the THDM for $m_{H^+} = 200$ GeV and $\tan\beta = 0.5, 1$, and 35.
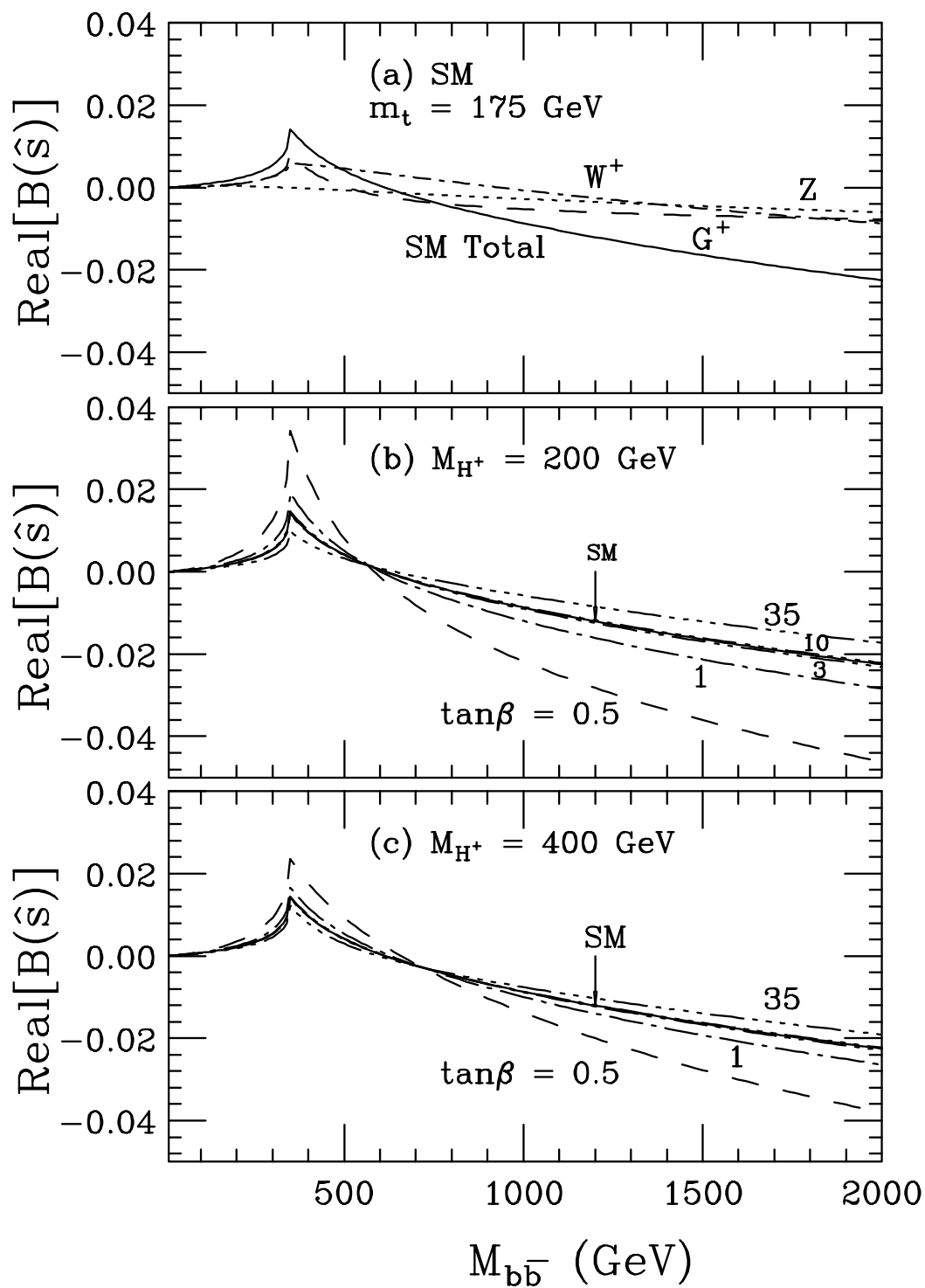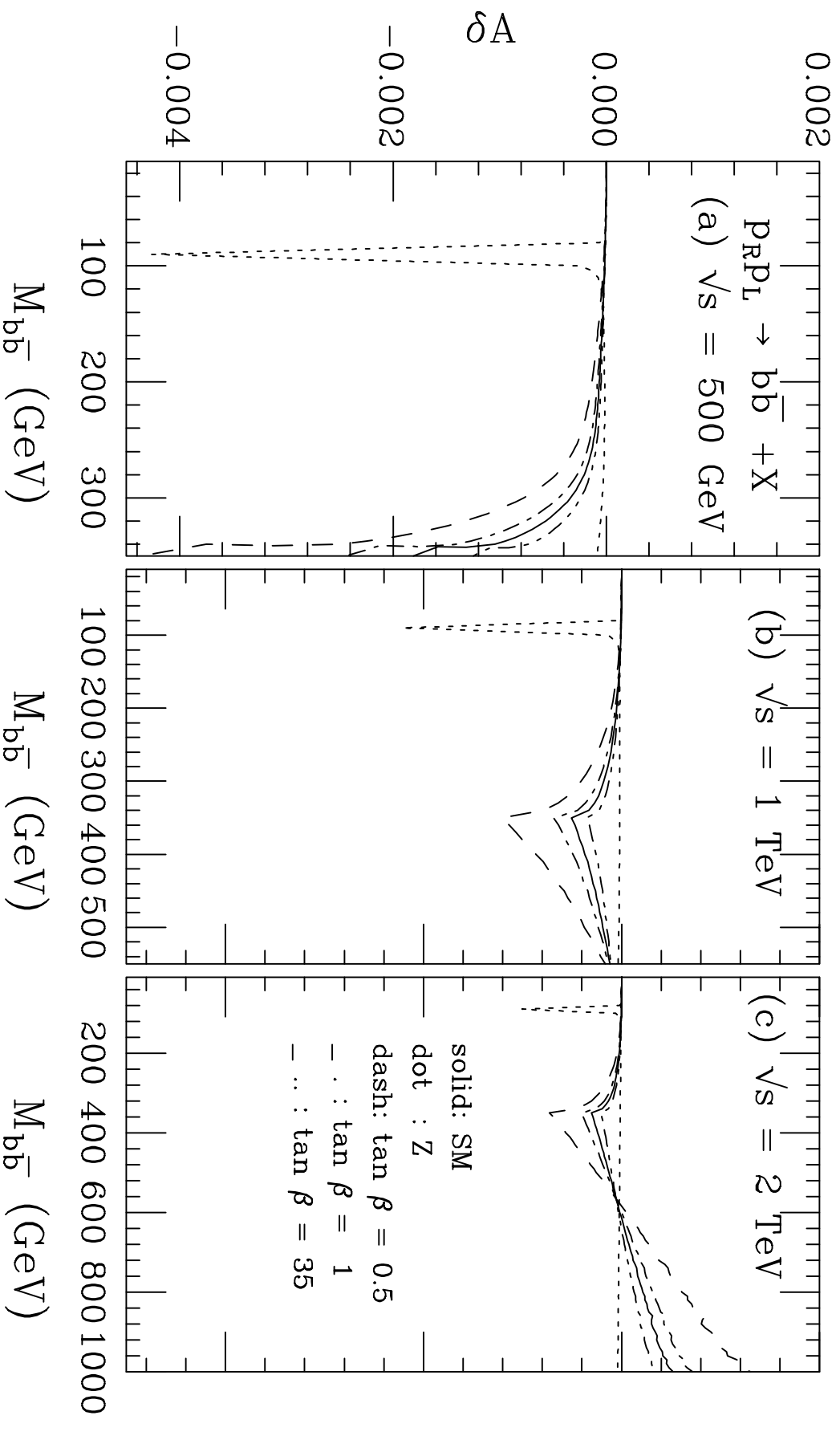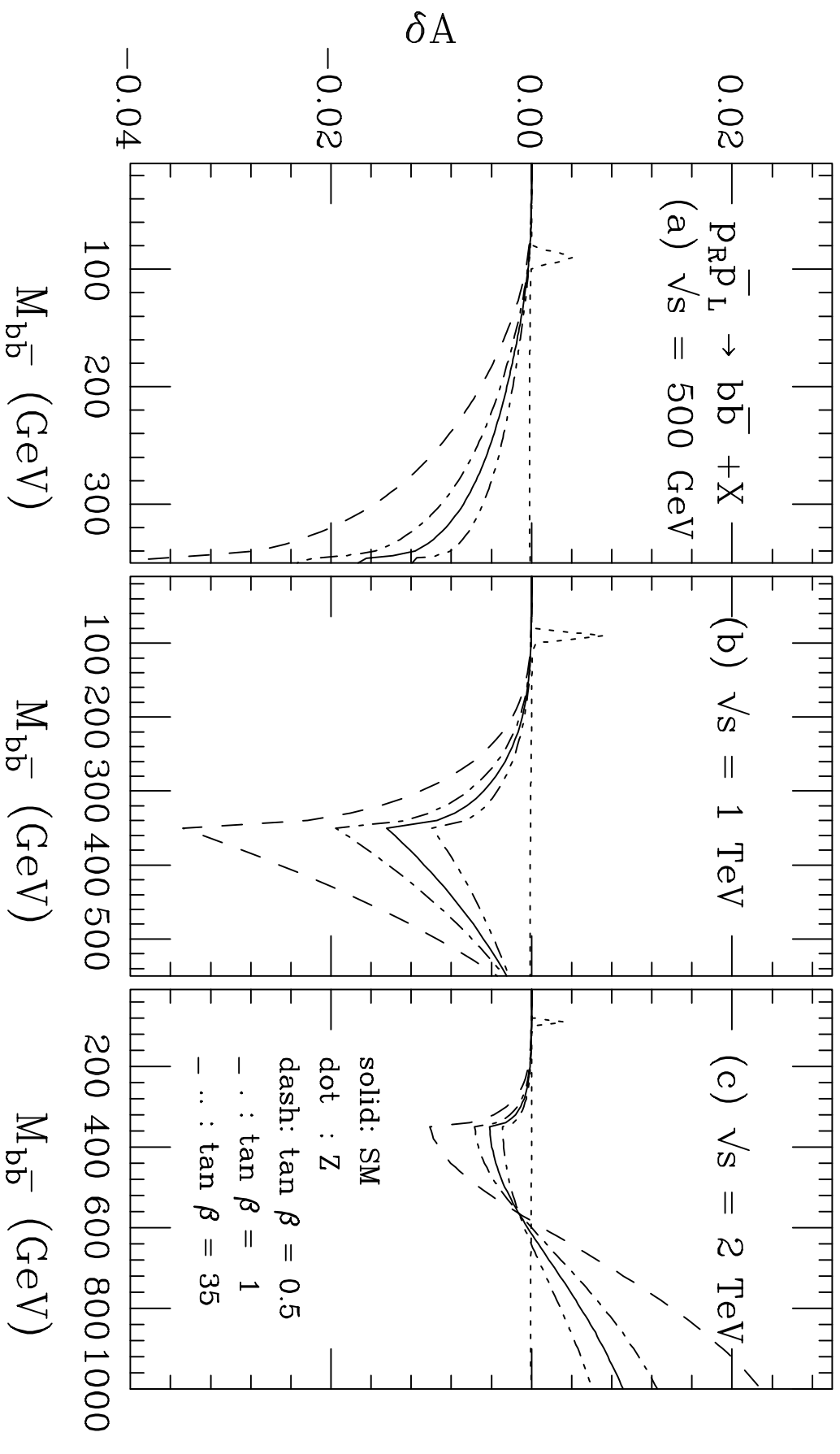
FIG 1/Atwood, Kao and Soni

FIG 2/Atwood, Kao and Soni

FIG 3/Atwood, Kao and Soni